

Formation of quarkonium states at RHIC

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Abstract. At RHIC the cross section for $c\bar{c}$ production will be large enough such that approximately 10 pairs will be produced in each central collision. If a region of deconfined quarks and gluons is subsequently formed, one would expect that the mobility of the charm quarks will enable them to form J/ψ through “off-diagonal” combinations, involving a quark and an antiquark which were originally produced in separate incoherent interactions. We present model estimates of this effect, which indicate that the signal for deconfinement at RHIC may possibly be J/ψ enhancement rather than suppression.

1. Introduction

A decrease in the number of observed J/ψ in heavy ion collisions due to the screening of the color confining potential was proposed many years ago [1] as a signature of a deconfined phase. It is argued that as the system cools and the deconfined phase disappears, these heavy quarks will most likely form a final hadronic state with one of the much more numerous light quarks. The result will be a decreased population of J/ψ relative to those formed initially in the heavy ion collision.

Here we study a scenario which can only be realized at RHIC (and LHC) energies, where the average number of initially-produced heavy quark pairs \bar{N}_0 is substantially above unity in each central collision. Then one can amplify the probability of J/ψ formation by a factor which is proportional to \bar{N}_0^2 , *if and only if a space-time region of deconfined quarks and gluons is present*. Realization of this result will depend on the efficiency of this new formation mechanism during the deconfinement period. We have developed a simple model to estimate the magnitude of this effect, and examined the sensitivity of results to various input parameters and assumptions.

2. Suppression Factor

For expected conditions at RHIC, almost all of the directly-produced J/ψ will be dissociated even in peripheral collisions. To include the effects of our new formation mechanism, we parameterize the final J/ψ number in each event as follows:

Of the N_0 charm quark pairs initially produced in a central heavy ion collision, let N_1 be the number of those pairs which form J/ψ states in the normal confining vacuum potential. At hadronization, the final number $N_{J/\psi}$ will contain a small fraction ϵ of the initial number N_1 . The majority of $N_{J/\psi}$ will be formed by this new mechanism which we expect to be quadratic in the remaining $N_0 - N_1$ heavy quark pairs, with a proportionality parameter β . (We include in the new mechanism both formation and

suppression effects, since they occur simultaneously in the deconfined region.) The final population is then

$$N_{J/\psi} = \epsilon N_1 + \beta(N_0 - N_1)^2. \quad (1)$$

For each N_0 initially-produced heavy quark pairs, we then average over the distribution of N_1 , introducing the probability x that a given heavy quark pair was in a bound state before the deconfined phase was formed. (This factor includes the effect of interactions with target and projectile nucleons). We finally average over the distribution of N_0 , using a Poisson distribution with average value \bar{N}_0 , to obtain the expected $\langle N_{J/\psi} \rangle$ final population per collision,

$$\langle N_{J/\psi} \rangle = x\bar{N}_0(\epsilon + \beta(1-x)) + \bar{N}_0(\bar{N}_0 + 1)\beta(1-x)^2. \quad (2)$$

The bound state “suppression” factor $S_{J/\psi}$ is just the ratio of this average population to the average initially-produced bound state population per collision, $x\bar{N}_0$.

$$S_{J/\psi} = \epsilon + \beta(1-x) + \beta \frac{(1-x)^2}{x} (\bar{N}_0 + 1) \quad (3)$$

Without the new production mechanism, $\beta = 0$ and the suppression factor is $S_{J/\psi} = \epsilon < 1$. (Even the fitted parameter ϵ contains some effects of the new mechanism, since formation can reoccur subsequent to the dissociation of an initial J/ψ . Here we use it as an upper limit with which to compare the complete result.) However, it is possible that for sufficiently large values of β and \bar{N}_0 this factor could actually exceed unity, i.e. one would predict an **enhancement** in the heavy quarkonium production rates to be the signature of deconfinement! We thus proceed to estimate expected β -values for J/ψ production at RHIC.

3. Model for J/ψ Formation

This model is adapted from our previous work on the formation of B_c mesons [2]. Initial results for the J/ψ application are found in Reference [3]. For simplicity, we assume the deconfined phase is an ideal gas of free gluons and light quarks. Any J/ψ in this medium will be subject to dissociation via collisions with gluons. (This is the dynamic counterpart of the plasma screening scenario, in which the color-confinement force is screened away in the hot dense plasma [4].) The primary formation mechanism is just the reverse of the dissociation reaction, in which a free charm quark and antiquark are captured in the J/ψ bound state, emitting a color octet gluon. Thus it is unavoidable for this model of quarkonium suppression that a corresponding mechanism for quarkonium production must be present. The competition between the rates of these reactions integrated over the lifetime of the QGP then determines the final J/ψ population. Note that in this scenario it is impossible to separate the formation process from the dissociation (suppression) process. Both processes occur simultaneously, in contrast to the situation in which the formation only occurs at the initial times before the QGP is present.

The time evolution if the J/ψ population is then given by

$$\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c \rho_{\bar{c}} - \lambda_D N_{J/\psi} \rho_g, \quad (4)$$

where τ is the proper time in a comoving volume cell and ρ_i denotes the number density [L^{-3}] of species i . The reactivity λ [L^3/time] is the reaction rate $\langle \sigma v_{\text{rel}} \rangle$

averaged over the momentum distribution of the initial participants, i.e. c and \bar{c} for λ_F and J/ψ and g for λ_D . The gluon density is determined by the equilibrium value in the QGP at each temperature. Exact charm conservation is enforced throughout the calculation. The initial volume at $\tau = \tau_0$ is allowed to undergo longitudinal expansion $V(\tau) = V_0\tau/\tau_0$. The expansion is taken to be isentropic, $VT^3 = \text{constant}$, which then provides a generic temperature-time profile. For simplicity, we assume the transverse spatial distributions are uniform, and use a thermal equilibrium momentum distribution for both gluons and charm quarks. (This last simplification requires large energy loss mechanisms for the charm quarks in the deconfined medium, which is indicated by several recent studies [5]).

With these inputs and assumptions, the solution of Equation 4 is precisely that anticipated in Equation 1, with

$$\epsilon(\tau_f) = e^{-\int_{\tau_0}^{\tau_f} \lambda_D \rho_g d\tau}, \quad (5)$$

where τ_f is the hadronization time determined by the initial temperature (T_0 is a variable parameter) and final temperature ($T_f = 150$ MeV ends the deconfining phase), and

$$\beta(\tau_f) = \epsilon(\tau_f) \times \int_{\tau_0}^{\tau_f} \lambda_F [V(\tau) \epsilon(\tau)]^{-1} d\tau. \quad (6)$$

For our quantitative estimates, we utilize a cross section for the dissociation of J/ψ due to collisions with gluons which is based on the operator product expansion [4, 6], which is utilized with detailed balance factors to calculate the primary formation rate for the capture of a charm and anticharm quark into the J/ψ .

4. Results

In Figure 1 we show the time development of the J/ψ (solid line) along with the separate formation and dissociation rates (dotted lines, arbitrary units).

This calculation maintained exact charm conservation, so that the solutions followed evolution of both bound and free charm quarks. One sees the expected decrease of the formation rate due to the volume expansion, and the decrease of the gluon dissociation rate due to the decrease in gluon density with temperature.

Some typical calculated values of the J/ψ final population are shown in Figure 2. The parameter values for thermalization time $\tau_0 = 0.5$ fm, initial volume $V_0 = \pi R^2 \tau_0$ with $R = 6$ fm, and a range of initial temperature $300 \text{ MeV} < T_0 < 500 \text{ MeV}$, are all compatible with expectations for a central collision at RHIC. The quadratic fits of Equation 1 are superimposed, verifying our expectations that the decrease in initial unbound charm is a small effect. (These fits also contain a small linear term for the cases in which N_1 is nonzero, which accounts for the increase of the unbound charm population when dissociation occurs.) The fitted ϵ values decrease quite rapidly with increasing T_0 as expected, and give reasonable upper limits for the suppression factor of directly-produced J/ψ in central collisions at RHIC due to gluon dissociation in a deconfined phase. The corresponding β values are relatively insensitive to T_0 , remaining in the range $2.0 - 2.6 \times 10^{-3}$. These fitted parameters must be supplemented by values of x and \bar{N}_0 to determine the “suppression” factor from Equation 3 for the new mechanism. We use $\bar{N}_0 = 10$ from a pQCD estimate [7]. An order of magnitude estimate of 10^{-2} for x , from fitted values of a color

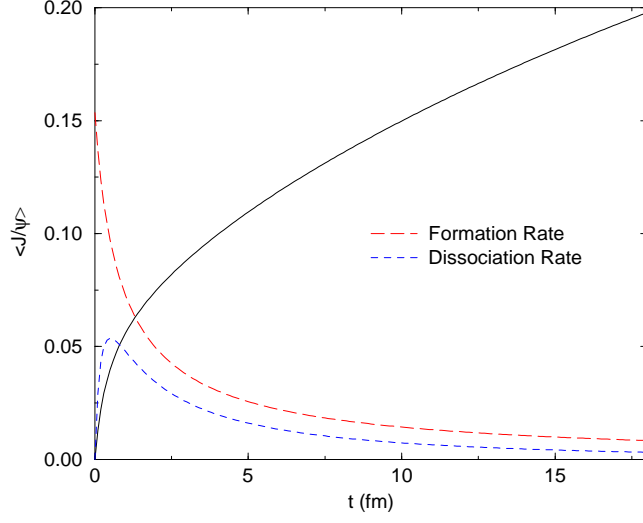


Figure 1. Time dependence of J/ψ formation including new mechanism.

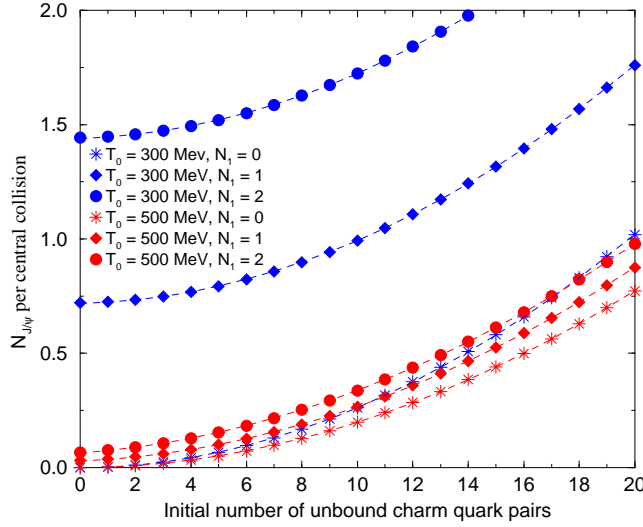


Figure 2. Calculated J/ψ formation in deconfined matter at several initial temperatures at RHIC, as a function of initial charm production.

evaporation model [8], is reduced by the suppression due to interactions with target and beam nucleons. For central collisions we use 0.6 for this factor, which results from the extrapolation of the observed nuclear effects for p-A and smaller A-B central interactions.

With these parameters fixed, we predict from Equation 3 an **enhancement** factor for J/ψ production of $3.6 < S_{J/\psi} < 5.4$, for initial temperatures between 300 and 500 MeV. The suppression of initially-produced J/ψ alone ranges from factors of 10 to 100, so that the enhancement prediction involves a huge increase (factors of approximately

one to two orders of magnitude) in the final population of J/ψ at RHIC.

5. Centrality Dependence

We also predict how this new effect will vary with the centrality of the collision, which has been a key feature of deconfinement signatures analyzed at CERN SPS energies [9]. The ϵ and β parameters are recalculated, using appropriate variation of initial conditions with impact parameter b . From nuclear geometry and the total non-diffractive nucleon-nucleon cross section at RHIC energies, one can estimate the total number of participant nucleons $N_P(b)$ and the corresponding density per unit transverse area $n_P(b, s)$ [10]. The former quantity has been shown to be directly proportional to the total transverse energy produced in a heavy ion collision [11]. The latter quantity is used, along with the Bjorken-model estimate of initial energy density [12], to provide an estimate of how the initial temperature of the deconfined region varies with impact parameter. We also use the ratio of these quantities to define an initial transverse area within which deconfinement is possible, thus completing the initial conditions needed to calculate the J/ψ production and suppression. The average initial charm number \bar{N}_0 varies with impact parameter in proportion to the nuclear overlap integral $T_{AA}(b)$. The impact-parameter dependence of the fraction x is determined by the average path length encountered by initial J/ψ as they pass through the remaining nucleons, $L(b)$ [13]. All of these b -dependent effects are normalized to the previous values used for calculations at $b = 0$.

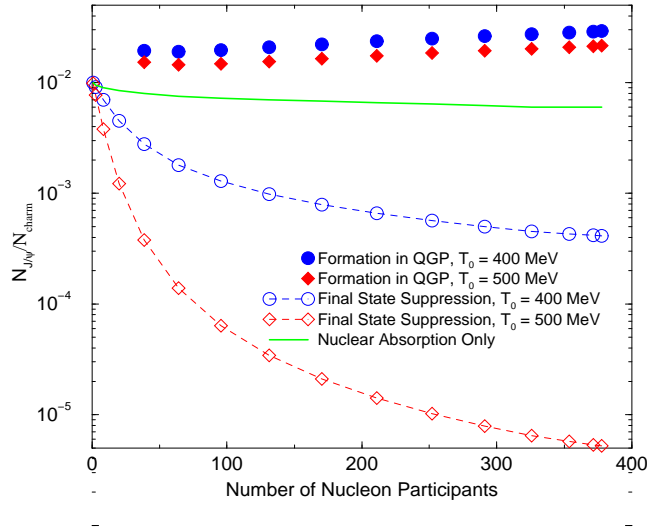


Figure 3. Ratio of final J/ψ to initial charm as a function of centrality, due to nuclear absorption only (solid line), after final state suppression by a QGP (dashed lines), and with inclusion of the new formation mechanism in the deconfined medium (solid symbols).

It is revealing to express these results in terms of the ratio of final J/ψ to initially-produced charm pairs. In Figure 3, the solid symbols are the full results predicted with the inclusion of our new production mechanism at RHIC. The centrality dependence is represented by the total participant number $N_P(b)$. For comparison we

also show predictions without the new mechanism, when only dissociation by gluons is included ($\lambda_F = 0$). It is evident not only that the new mechanism dominates the J/ψ production in the deconfined medium at all impact parameters, but also that an increase rather than a decrease is predicted for central collisions. These features should be distinguishable in the upcoming RHIC experiments.

6. Model Dependence

In our model of a deconfined region, we have used the vacuum values for masses and binding energy of J/ψ , and assumed that the effects of deconfinement are completely included by the dissociation via gluon collisions. For a complementary viewpoint, we have also employed a deconfinement model in which the J/ψ is completely dissociated when temperatures exceed some critical screening value T_s . Below that temperature, the new formation mechanism will still be able to operate, and we use the same cross sections and kinematics. We find that for $T_s = 280$ MeV, the final J/ψ population is approximately unchanged, while decreasing T_s to 180 MeV could reduce the J/ψ production by factors of 2 or 3. These results are shown in Figure 4.

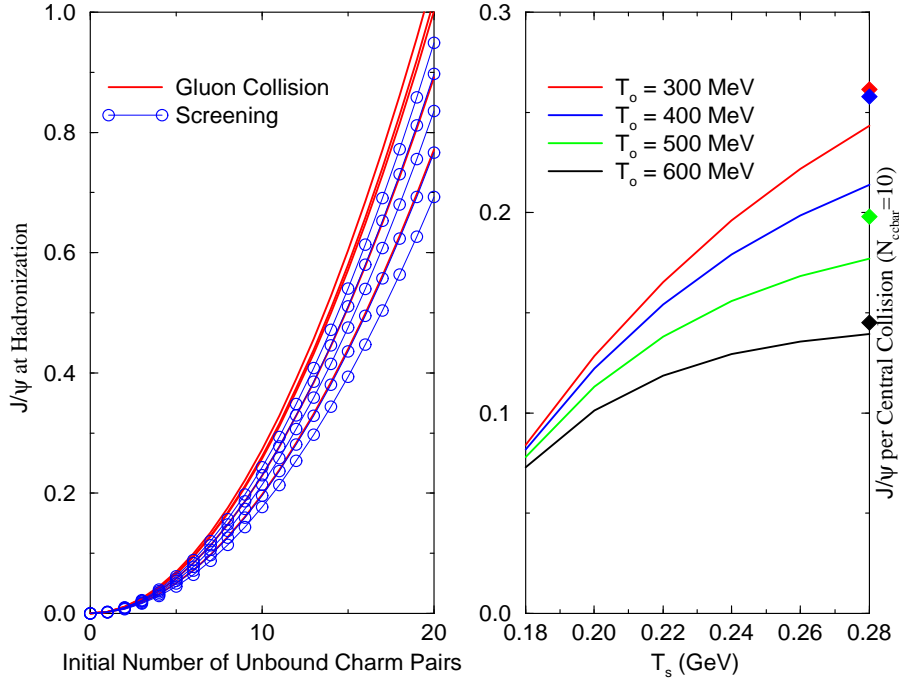


Figure 4. Comparison of Gluon Dissociation and Screening Scenarios for J/ψ formation including new mechanism (see text for details).

We have also checked the sensitivity of these results to several other assumptions and parameters. Among these are: (a) Change in initial charm production due to gluon shadowing; (b) Alternative cross sections with different magnitudes and threshold behaviors; (c) Transverse expansion of the QGP; (d) Non-chemical equilibrium for gluons; (e) Non-thermal momentum distributions for charm quarks. The effects of

varying these assumptions produce both positive and negative changes in the final J/ψ populations. The largest effect could be a decrease by a factor of 2 or 3 if one uses the initial pQCD momentum distributions for the charm quarks. Taken together, however, it is unlikely that a conspiracy of these effects would qualitatively change the predicted enhancement effects of this deconfinement scenario.

7. Summary

In summary, we predict that at RHIC energies the J/ψ production rate will provide a more interesting signal for deconfinement than has been previously realized. Consideration of multiple heavy quark production made possible by higher collision energy effectively adds another dimension to the parameter space within which one searches for patterns of quarkonium behavior in a deconfined medium. It will be possible to experimentally “tune” the number of initial heavy quark pairs by sweeping through either centrality or energy. One can then search for a J/ψ production behavior which is predicted to be nonlinear in total charm. In our simplified kinetic model of J/ψ formation in a free gas of quarks and gluons, the new production mechanism predicts an enhancement rather than a suppression. These features should provide a signal at RHIC which will be difficult to imitate with conventional hadronic processes. The extension of this scenario to LHC energies will involve hundreds of initially-produced charm quark pairs and multiple bottom pairs. We expect the effects of this new production mechanism to be striking.

Acknowledgments

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